EFFECTS OF CONVECTIVE OVERSHOOTING IN THE PMS EVOLUTION OF INTERMEDIATE MASS STARS

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Abstract

We discuss the new results on the effects of convective overshooting in the PMS evolution of intermediate mass stars. These effects are extremely important in the end of the PMS, when the abundances in CNO elements approach the equilibrium in the centre. A moderate amount of overshooting produces, as the star approaches the ZAMS, an extra loop in the evolutionary tracks on the HR diagram; the amount of overshooting needed to produce the loop decreases with the stellar mass.

An interesting feature is that there is a very well defined amount of overshooting (for a given stellar mass and chemical composition) beyond which a loop is produced; for smaller amounts of overshooting such a loop does not take place and the evolutionary tracks are similar to the ones obtained by Iben (1965).

We discuss the reasons for this behaviour and argue that it can provide a crucial observational test for convective overshooting in the core of intermediate mass stars.

Key words: Stars: structure – stars: pre-main sequence – stars: evolution – stars: interiors – convection

1. Convective overshooting

It is generally assumed that the boundary between regions where convective motions are present and absent (M_{bc}) is determined by the instability criteria, but these determine only the boundary between regions where buoyancy forces favor convection and regions where they do not. Convective elements that reach the boundary with non-zero velocities overshoot it, reaching a region where $\nabla < \nabla_{\mathrm{ad}}$. They are therefore colder than their surroundings, absorbing energy: convective elements that overshoot the boundary given by the instability criteria transport energy inwards. To transport all the energy generated in the convective core outwards, the luminosity transported by radiation in the zone imediately above the boundary must be superior to the total luminosity, that is, in this zone one must have $\nabla > \nabla_{\mathrm{rad}}$.

The problem of how much is the amount of overshooting generated this way is still far from solved (see for example Renzini 1987). Works dedicated to this subject came out with answers ranging from almost insignificant overshooting to quite high. We use a prescription (see Maeder 1975 and Mowlavi & Forestini 1994) that consists of considering that the extent of the overshooting from the core is given by

$$d_{\mathrm{ov}} = \alpha_{\mathrm{ov}} \times \mathrm{Min}\left(H_P, r_{\mathrm{co}}\right), \tag{1}$$

where H_P is the pressure scale height ($H_P = |\mathrm{d}r/\mathrm{d}\ln P|$), r_{co} is the radius of the convective core and α_{ov} is a free parameter (d_{ov} is not simply proportional to H_P because this quantity becomes infinite in the centre). Then, inside $r_{\mathrm{co}} + d_{\mathrm{ov}}$ there is complete mixing and the stratification is adiabatic ($\nabla = \nabla_{\mathrm{ad}}$); we shall call this zone the mixed zone (MZ). Inside r_{co} (given by the instability criteria), energy is transported by convection; this is the convective zone (CZ).

As stars evolve during the PMS, their central temperatures and densities rise, until they are high enough for nuclear reactions to start. Nuclear reactions start by stages: first, deuterium is burned, then lithium and, towards the end of the PMS phase, ^{12}C (roughly when the other reactions of the PP chains start). The harder reaction of the CNO cycle is the ^{14}N-burning, so almost all the original ^{12}C is burned in ^{14}N when abundances in CNO elements reach equilibrium. If the star is massive enough to burn ^{14}N efficiently, the CNO cycle takes over the energy production, together with the PP chains. Otherwise, only PP chains contribute significantly to the energy production. The burning of ^{12}C, being so strongly dependent on temperature, is highly concentrated towards the centre of the star. Radiation alone can not transport the energy produced in such a small volume outwards: a central convective zone appears. The purpose of this work is to study the effects of overshooting from this convective core.

2. Effects of convective overshooting

We produced evolutionary sequences of models in the PMS phase. Models were computed using the CESAM stellar evolution code (Morel 1997). Typically, each model is described by about 600 shells, and an evolution by about 400–600 models. The maximum time step of the evolution is given by:

$$\Delta t = 0.1 (M/M_{\odot})^{-2.5}. \tag{2}$$

Each evolution is initialized with an homogeneous, fully convective model in quasi-static contraction, with a central temperature inferior to the ignition temperature of deuterium. We shall call the "age" of the model the time elapsed since initialization.

The model of zero-age main-sequence is defined as the first model where nuclear reactions account for more than 99% of the energy production.

We used the OPAL equation of state (Rogers & Iglesias 1996) and the opacities of Iglesias & Rogers (1996) complemented, at low temperatures, by the Alexander & Fergusson (1994) opacities.

The temperature gradient in convection zones is computed using the standard mixing-length theory. The mixing length is defined as $l = \alpha H_P$.

The nuclear network we used contains the following species: ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{7}Li, ^{7}Be, ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O, ^{17}O, ^{9}Be and a extra fictitious non-CNO heavy element which complements the mixture; this element has atomic mass 28 and charge 13. Deuterium and lithium burning are taken into account, as well as the most important reactions of the PP+CNO cycles. The nuclear reaction rates are taken from the NACRE compilation (Angulo et al. 1999). We do not consider diffusion processes due to the young ages of the stars considered.

2.1. The case of a $1M_\odot$-star

We have produced models of a $1M_\odot$ star using an initial helium abundance $Y_\mathrm{i} = 0.28$, initial metalicity $Z_\mathrm{i} = 0.02$ and mixing length parameter $\alpha = 1.35$. We considered two cases: $\alpha_\mathrm{ov} = 0$ and $\alpha_\mathrm{ov} = 0.10$.

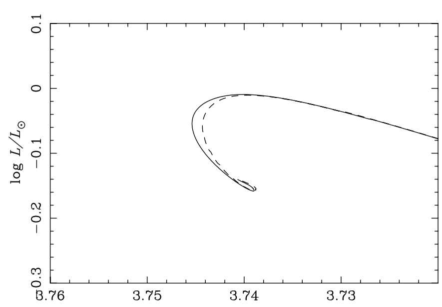

Figure 1. Evolutionary tracks in the HR diagram for a $1M_\odot$ star with $\alpha_\mathrm{ov} = 0$ (full line) and $\alpha_\mathrm{ov} = 0.1$ (dashed line).

Fig. 1 shows that the effect of the overshooting in the evolutionary tracks on the HR diagram is to make the final drop in luminosity more abrupt. This is caused by the greater extent of the CZ with $\alpha_\mathrm{ov} = 0.10$. The CZ is bigger with overshooting because there is more ^{12}C to burn (since the MZ is extended by overshooting). This can be seen comparing Figs 2 (showing the extent of the CZ) and 3 (showing the evolution of the abundances in CNO elements). The central CZ disappears much later in the evolution when there is overshooting: while the central CZ is gone at an age of 90 Myrs without overshooting, it disappears only at an age of 170 Myrs with $\alpha_\mathrm{ov} = 0.10$. The burning of ^{12}C takes longer not only because there is a greater amount to burn but also because the burning rate is lower since in a convective core the central density (and also the central temperature) is lower than in a radiative core.

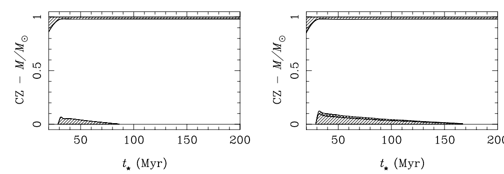

Figure 2. Evolution of the convective zones (hached area) of a $1M_\odot$ star with $\alpha_\mathrm{ov} = 0$ (left panel) and $\alpha_\mathrm{ov} = 0.10$ (right panel). Cross-hatched areas represent the MZ extended by overshooting.

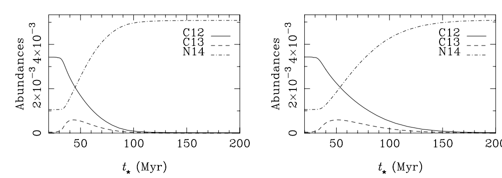

Figure 3. Evolution of the central abundances in CNO elements in a $1M_\odot$ star with $\alpha_\mathrm{ov} = 0$ (left panel) and $\alpha_\mathrm{ov} = 0.1$ (right panel).

2.2. The case of a $2M_\odot$-star

We have also produced models of a $2M_\odot$ star using the same physical inputs and parameters as in the previous case, with α_ov varying from 0 to 0.20. The most remarkable feature is that there are two kinds of tracks, with or without a "loop" just before the ZAMS. The transition between these two kinds of tracks happens at a very definite value of α_ov, as seen in Fig. 4: for $\alpha_\mathrm{ov} = 0.1360$ there is no "loop" in the evolutionary tracks on the HR diagram (for this stellar mass), while there is a "loop" for $\alpha_\mathrm{ov} = 0.1361$. For values of α_ov lower than 0.1360, the tracks do not differ significantly; the same happens for values of α_ov higher than 0.1361.

As shown in Fig. 5, the difference between these two kinds of evolution is the sudden growth of the central MZ after the first minimum. This is caused by the very steep growth of the production of energy through ^{12}C-burning.

When the central MZ grows after reaching its first minimum (as the central temperature and density rise, the

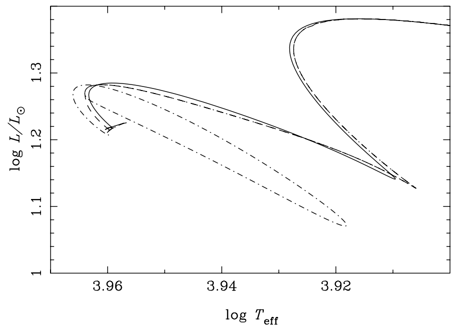

Figure 4. Evolutionary tracks in the HR diagram for a $2M_\odot$ *star with* $\alpha_{\rm ov} = 0$ *(full line),* $\alpha_{\rm ov} = 0.1360$ *(dashed line) and* $\alpha_{\rm ov} = 0.1361$ *(dot-dashed line).*

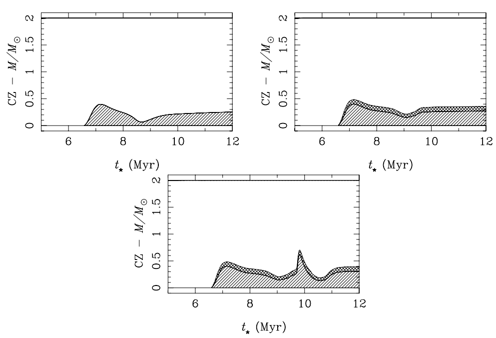

Figure 5. Evolution of the convective zones (hached area) of a $2M_\odot$ *star with* $\alpha_{\rm ov} = 0$ *(left panel),* $\alpha_{\rm ov} = 0.1360$ *(right panel) and* $\alpha_{\rm ov} = 0.1361$ *(lower panel). Cross-hatched areas represent the MZ extended by overshooting.*

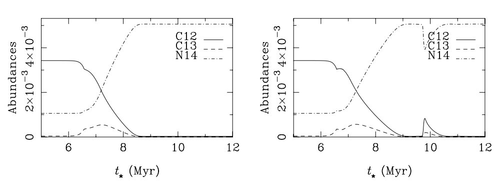

Figure 6. Evolution of the central abundances in CNO elements in a $2M_\odot$ *star with* $\alpha_{\rm ov} = 0$ *(left panel) and* $\alpha_{\rm ov} = 0.1361$ *(right panel).*

burning of ^{14}N becomes efficient enough and the energy production becomes very concentrated towards the centre again), it englobs regions where ^{12}C was not completed burned when the MZ reached those regions. This fresh ^{12}C is burned at a much faster rate than before, since the central temperature and density are much higher now. Without overshooting, ^{12}C is burned at the same rate it is englobed by the growing MZ (see Fig. 6). This does not happen when $\alpha_{\rm ov} \geq 0.1361$.

3. Discussion

The essential feature to appear with overshooting for a $2M_\odot$ star is the fact that it extends the MZ towards regions with lower temperature. When there is enough overshooting, the temperature at the boundary of the MZ becomes so low that no more ^{12}C is burned above it. When the MZ grows again, it finds fresh ^{12}C to burn, which would not happen whithout overshooting (the temperature above the MZ would be always high enough to burn ^{12}C above the MZ as it grows for the last time, reducing the amount of ^{12}C that would be englobed). This becomes clear considering Fig. 7. Fig. 7 shows that the amount of overshooting needed to lower the temperature of the boundary of the MZ below the ignition temperature of ^{12}C is near $\alpha_{\rm ov} = 0.136$, which is around the value needed to produce a “loop” in the evolutionary track on the HR diagram.

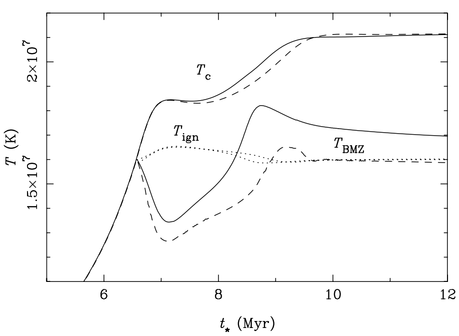

Figure 7. Evolution of the central temperature ($T_{\rm c}$) and the temperature of the boundary of the MZ ($T_{\rm BMZ}$) for $\alpha_{\rm ov} = 0$ *(full line) and* $\alpha_{\rm ov} = 0.1360$ *(dashed line). Also shown is the ignition temperature for* ^{12}C *at the densities of the BMZ (dotted lines).*

The fact that the MZ englobes more fresh ^{12}C with overshooting means that this ^{12}C has to be burned at a faster rate, and the energy released causes the MZ to grow at a faster rate, bringing in turn ^{12}C to the centre at an even faster rate. On the other hand, the fact that the MZ is bigger with overshooting means that the burning of ^{12}C, being so concentrated towards the centre, is not so efficient in reducing the abundance of ^{12}C there. When $\alpha_{\rm ov}$ is high enough, the ^{12}C brought to the centre by the expanding MZ can not be burned at the same rate; the abundance in ^{12}C in the centre grows, which, at the present central temperature and density, results in a runaway growth in the energy production, causing in turn a growth in the central MZ and the “loop”.

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